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A comprehensive procedure for performance evaluation of solar food dryers

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Abstract

Solar food dryers are available in a range of size and design and are used for drying various food products. Testing a dryer is necessary to evaluate its absolute and comparative performance with other dryers and the test results provide relevant information for the designer as well as the user. Literature reviews on existing testing procedures reveal that a comprehensive procedure for evaluating the performance of solar food dryers is not available. Therefore, selection of dryers for a particular application is largely a decision based on what is available and the types of dryers currently used widely. This paper presents a detailed review of parameters generally used in testing and evaluation of different types of solar food dryers. The inadequacies of the parameters generally reported are highlighted and additional parameters have been suggested. Based on this review, a procedure has been proposed, giving the methodology, test conditions and a sample evaluation sheet. This would assist in an unambiguous evaluation of solar dryer performance and facilitate comparing different solar food dryers.

Contents

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1. Introduction

Drying agricultural products enhances their storage life, minimises losses during storage, and saves shipping and transportation costs. Conventional drying processes range from natural sun drying to industrial drying. Kiebling [1] has listed 66 different solar dryers, their configurations, capacity, products dried and cost. Fuller [2] and Ekechukwa and Norton [3] have reviewed many solar dryers, and compared their performance and applicability in rural areas. Most solar dryers developed are designed for specific products or class of products. Vegetables such as chilli, cassava,

Nomenclature

A	Aperture area of the dryer (m^2);
DHC	Dry matter holding capacity;
h_i	Absolute humidity of air entering the drying chamber (%);
h_o	Absolute humidity of air leaving the drying chamber (%);
h_{as}	Absolute humidity of the air entering the dryer at the point of adiabatic saturation (%);
I	hourly average solar radiation on the aperture surface (kWh);
L	Latent heat of vaporisation of water at exit air temperature (J/kg);
LCV	Lower calorific value of fuel (J/kg);
M	Mass (kg);
m_b	Mass of fuel consumed (kg);
P_f	Energy consumption of fan/blower (kWh or J);
Q_a	Energy absorbed by the drying air (kWh or J) ($mC_p\Delta T$);
Q_c	Solar radiation striking the collection area (kWh or J);
RC	Rehydration capacity;
s	Dry matter content (%);
t	Drying time (seconds);
V	Volumetric airflow rate (m^3/s);
W	Weight of water evaporated from the product (kg);
WAC	Water absorption capacity;
ρ	Density of air (kg/m^3);
η_{hc}	Heat collection efficiency;
η_p	Pick-up efficiency;
η_s	Drying system efficiency;Subscripts
d	dry;
o	original (before drying);
r	rehydrated.

onion, radish, ginger, peas, corn, mushroom, tamarind and coconut, and fruits such as mango, apple, pineapple, banana, grapes, prunes and longans are commonly dried in Asia [4,5]. Selection of a solar dryer for a particular food product is determined by quality requirements, product characteristics and economic factors. A systematic classification of available solar food dryers, based on the design of system components and the mode of utilisation of solar energy, is presented in Fig. 1.

Testing a dryer is necessary to evaluate its technical performance and thus provides a basis to compare it with other dryers. This would also assist manufacturers in improving dryer designs, and users in selecting appropriate dryers. Performance evaluation also enables predicting the performance of a dryer under conditions which are different from test conditions [6].

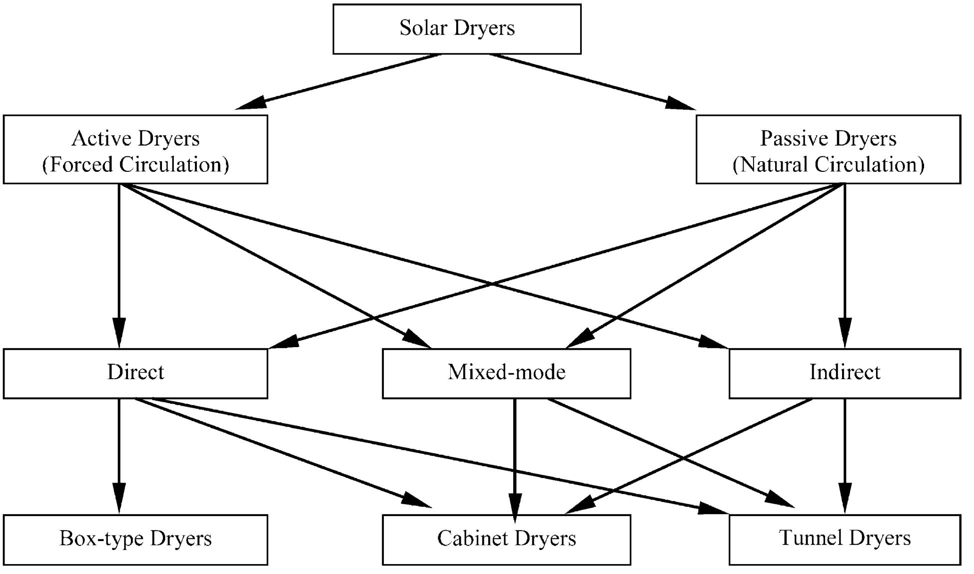

Fig. 1. Classification of solar dryers and drying modes.

This paper first presents a review of existing evaluation methods and the parameters generally considered for the evaluation of solar food dryers. Based on the review, a comprehensive testing and evaluation procedure for solar food dryers, with details of all useful parameters necessary to evaluate solar dryer performance is proposed.

2. Current methods of testing and evaluation

The drying process involves simultaneous: (i) heat transfer from the surrounding to the surface of the product being dried combined with heat transmission within the material; and (ii) mass transfer from inside the product to its surface, followed by external transport of moisture to the surroundings [7]. Parameters of the product such as the physical properties (size, density etc.), moisture content and mass–heat transfer coefficients between the air and the food product, all vary during the drying process. This is further influenced by the conditions external to the product such as temperature, humidity and flow rate of the drying air and also by changes in the chemical composition of the food product [8]. Each product tolerates a maximum temperature dependent on its type (vegetable, fruit, cereal etc.), use, moisture content and degree of maturity [9].

Standard test procedures for solar components, such as collectors, and systems such as solar air and water heaters are available [10–13]. However, standard test procedures for evaluating the performance of solar dryers are not available [6]. This is largely due to variations in dryer design, construction materials, operating con-

ditions, consumer preferences and quality interpretations. A few authors have, however, attempted to follow a procedure while reporting evaluation results of solar dryers [6,14].

Grupp et al. [14] have presented a method of evaluating and comparing solar dryers. The purpose of the tests was mainly to assess different dryers from the users' perspective. They conducted tests on six different types of solar dryers (a circular box-type dryer, a shell dryer, a cabinet dryer, a tunnel dryer and two chimney dryers) at Plataforma Solar de Almeria in Spain. The parameters reported were the physical dimensions and type of dryer, solar aperture, tray area, drying time and temperature, moisture content, dried product quality and handling convenience. Red pepper, green pepper and parsley were used as reference products for the drying tests. The products were also sun-dried simultaneously in blackened concrete, untreated concrete and in a tray placed on the ground. The experimental observations of the parameters were then used to compare different dryers and an overall grading was awarded to the tested dryers. The tunnel dryer scored highest in terms of overall performance, while open sun drying was rated worst, mainly because of the bad quality of the dried products due to contamination, poor colour, aroma and taste. Based on the test results, the authors also proposed specific design improvements that could be carried out on the tested dryers.

Sodha and Chandra [6] have presented various testing methods for evaluating the comparative and absolute thermal performance of solar collectors. The common procedures include the National Bureau of Standards (NBS, USA), American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) and Bundesverband Solarenergie or Federal Association for Solar Energy (BSE, Germany) test procedures. The authors suggest cost, lifetime, durability, maintenance and installation as the additional parameters to be evaluated in solar dryers. Other publications (described in Table 1) present an assessment of solar food dryers based on only a few specific parameters. In general, no particular procedure is followed in these assessments and dryers are evaluated by measuring and comparing certain selected parameters. In most cases, these are related to only the thermal performance of the dryers. Section 3 deals with these parameters in detail.

The absence of reliable evaluation procedures for solar food dryers has often led to the selection of dryers based on what are commonly in use [15]. This results in selection of dryers which may not be suitable for the particular product to be dried or for specific operating conditions.

Reddy [16] notes that laying down rigid standard tests for solar systems in order to improve system design and performance would require too many experiments, which are time-consuming and expensive. Therefore, the standards must be versatile enough to take into account differences in design and operation from one type of dryer to another, but should also not be too elaborate, as that would make the testing process too laborious as well as expensive.

Table 1
Summary of solar dryer evaluation parameters and results in the literature

Author(s)	Test Parameters									
	Drying time/rate	Drying temp.	Airflow rate	Drying capacity	Quality of dried product	Energy consumption for drying	Cost of dryer/ payback	Temperature and/or R.H of exit air	Loading/ unloading convenience	Others
Arinze et al., 1999 [54]	✓	✓	✓	✓	✓	✓	✓	✓	–	Collector efficiency
Das and Kumar, 1989 [55]	✓	✓	✓	✓	✓	–	–	✓	–	–
Esper et al., 1996 [56]	✓	–	✓	✓	✓	–	✓	–	–	–
Fuller et al., 1990 [57]	–[d]	✓	✓	✓	✓	–	–	–	–	–
Fuller, 1995 [2]	✓	✓	✓	✓	–	✓	–	–	–	–
Gallali et al., 1999 [48]	✓	✓	–	–	✓	–	–	–	–	Sensory evaluation[a]; chemical analysis[b]
Gnanaranjan et al., 1997 [58]	✓	✓	✓	✓	✓	✓	✓	–	–	–
Grupp et al., 1995 [14]	✓	✓	✓	✓	✓	–	✓	–	✓	Tray area; drying temperature control
Janjai et al., 1998 [59]	✓	✓	–	✓	✓	–	✓	✓	-	–
Mande et al., 1993 [60]	✓	✓	✓	✓	✓	✓	–	–	–	Thermal efficiency
Martinez, 1989 [61]	✓	–	–	✓	–	–	–	–	–	Collector area
Mastekbayeva et al., 1998[27]	✓	✓	✓	✓	✓	–	✓	✓	–	–
Moyls, 1986 [62]	✓	–	✓	✓	–	–	–	–	–	–
Pairintra et al., 1996 [63]	✓	✓	✓	✓	–	✓	✓	–	–	–
Pengpad and Rackwichian, 1998 [29]	✓	✓	✓	✓	✓	✓	–	–	✓	Drying efficiency; SMER[c]
Rahardjo et al., 1983 [64]	✓	✓	✓	✓	✓	–	–	–	–	–
Rakwichian et al., 1998 [43]	✓	✓	✓	✓	–	✓	–	✓	–	Collector & dryer effy; fuel savings
Schirmer et al., 1996 [65]	✓	✓	✓	✓	✓	–	✓	✓	–	–
Sharma et al., 1986 [66]	✓	✓	✓	✓	–	✓	–	✓	–	–
Sharma et al., 1995 [67]	✓	✓	–	✓	✓	–	✓	–	–	–
Sithiphong et al., 1985 [68]	✓	–	–	✓	–	✓	–	–	–	–
Soponronnarit and Assayo, 1991 [69]	✓	✓	✓	✓	✓	✓	✓	–	–	Drying system efficiency
Soponronnarit et al., 1993 [46]	✓	✓	✓	✓	✓	✓	✓	–	–	Specific energy consumption

[a] Colour, flavour and texture of the dried product
[b] Ash, sugars, ascorbic acid or Vitamin C, and acidity contents
[c] Specific Moisture Extraction Rate
[d] Not reported

3. Parameters considered in the evaluation of solar dryers

Information on performance evaluation of common industrial dryers is available in the literature [17–19]. Sokhansanj and Jayas [20] note that the parameters significantly influencing dryer performance are:

1. drying air characteristics (drying air temperature, humidity and airflow rate);
2. product variables (product throughput, initial and final moisture contents, product size and size distribution); and
3. dimensional variables (width, length, height or diameter of the dryer, number of passes and dryer configuration).

Evaluation of solar dryer performance considers these various parameters.

According to Nonhebel [21], the selection of a dryer represents a compromise of dryer cost, product quality, safety considerations and convenience of installation.

3.1. Parameters generally reported

In the evaluation of solar dryers, the parameters generally measured and reported could be categorised as follows:

■ Physical features of the dryer
- Type, size, shape
- Drying capacity/loading density
- Tray area and number of trays (as applicable)
- Loading/unloading convenience

■ Thermal performance
- Drying time/drying rate
- Drying air temperature and relative humidity
- Airflow rate
- Dryer efficiency

■ Quality of dried product
- Sensory quality (colour, flavour, taste, texture, aroma)
- Nutritional attributes
- Rehydration capacity

■ Cost of dryer and payback period

3.1.1. Physical features of the dryer

These refer to the type, weight, dimensions and construction materials of the dryer. Though wood and metals are the common construction materials, cement and mortar are also used [3]. Solar collectors are usually constructed as bare-plate absorbers made of aluminium, galvanised iron or steel, and painted with a non-reflecting (matt

finish) black paint. Corrugated metal sheets (e.g. roofing sheets) are also used [22]. Selectively coated absorber sheets are used when the required temperature rise exceeds 40°C [23].

Glass and commercial non-glass glazing materials such as Tedlar (Poly Vinyl Fluoride), Suntek (Flourinated Ethylene Propylene/FEP Teflon), Novolux, Polyethylene Terephthalate (PET), Mylar (Polyester), polyethylene, PVC and plastic sheets (e.g. polycarbonate/plexiglass) are the common glazing materials used [23]. Insulation materials used for solar dryers include glasswool, rockwool, coir mattress, plywood, hay, ricehusk and sawdust [24]. Stainless steel, galvanised steel or nylon wire mesh is used to fabricate the trays on which the products to be dried are loaded.

The physical size of a dryer is often a direct measure of the drying capacity, which usually means batch drying capacity, and refers to the quantity dried in a single batch of loading, measured in kg of fresh product per batch. Throughput of a dryer is the rate at which the wet product can be dried to a required specific moisture content, usually expressed in kg fresh product per day [25]. For a given dryer, the drying capacity varies with the type of product and the amount of moisture to be removed. Generally, the size of the dryer indicates its drying capacity. Tray area indirectly refers to the loading or drying capacity of the dryer. Since the products need to be spread in a single layer for efficient drying, total tray area available in the dryer for spreading the product is important. In the case of cabinet type dryers, which have more than one layer of trays, number of layers will be an additional parameter which needs to be indicated. The conditions of drying air, flow rate and the product loaded will determine the number of tray layers for a particular dryer. Dryer capacity also depends on the aperture area or collector area and the size of the drying chamber.

Loading density determines the capacity of a dryer (together with total tray area and drying time) for a particular product. Placing products one above the other rather than a single layer tends to limit the area of exposure of product surfaces to drying air, resulting in poor drying [26]. Over-loading also influences the quality of dried product. On the other hand, part loading leads to low drying efficiencies due to non-optimal utilisation of aperture area [27]. Loading density depends on the type of product, its moisture content and airflow rate, and may be assessed based on the following rules of thumb [28]:

- Average dryer loading: 4 kg of fresh produce per square meter of tray area
- Solar collector size: 0.75×total tray area
- Airflow rate: 0.75 cubic meters per minute per square meter of tray area.

Pengpad and Rakwichian [29] note that loading/unloading of drying/dried products is important in commercial dryers due to possibilities of contamination and cost of labour. Handling convenience is also important, especially with fruits such as banana, where the possibilities for contamination are high with frequent loading and unloading. This problem could be avoided by using a continuous drying system (though this is possible mostly with hybrid operation) where fresh products are loaded at one end and the dried ones unloaded at the other end [29,30]. High labour

cost for loading and unloading is also associated with the handling convenience of a dryer.

3.1.2. Drying time/drying rate

The duration of the drying process is the most important parameter to be considered in evaluating a dryer. It is estimated from the time when the dryer is loaded with fresh product until when the product dries to the required moisture level, usually given as hours or days. The time period when solar radiation is not available is also usually included in drying time. While higher drying temperatures quicken the drying process, it could also cause damage to the product (loss of colour, flavour, aroma and vitamins).

Graphical representation of drying, with product moisture content and time as coordinates, indicates drying rate. Data from the different types of dryers plotted on the same graph give a comparative evaluation of dryer performance. In big dryers, it is important to check the uniformity of drying by analysing the drying rates of product samples kept at various locations on the tray(s).

Drying times may be considerably reduced by reducing the dimensions of the product dried (e.g. whole banana and sliced banana). The presence of a small amount of sulfite in a blanched, cut vegetable makes it possible to increase the drying temperature, thus shortening the drying time [31]. Chemical pre-treatment of products (e.g. grapes) to increase the water permeability of the skin significantly increases the drying rate [8,32].

3.1.3. Drying air temperature and relative humidity

Increasing the temperature of the drying air will increase the drying rate in two ways. First, this increases the ability of drying air to hold moisture. Secondly, the heated air will heat the product, increasing its vapor pressure. This will drive the moisture to the surface faster [28]. However, there is a limit to raising the temperature of air in a dryer. Operation of dryers at high temperatures is commonly constrained by the thermal sensitivity of most fruits and vegetables. If the temperature is too high in the beginning, a hard shell (dry layer) may develop on the outside (known as case hardening) trapping moisture inside the shell [33]. Temperatures that are too high at the end of the drying period may cause food to scorch. Irreversible changes of colloidal components of fruit/ vegetable tissue occur if the product is held for prolonged periods at high temperature, even if the exposure is insufficient to produce browning or scorching. The elasticity of cell walls and the swelling power of starch gel, both important for good rehydration, are reduced by high temperature exposure [26]. A high drying air temperature could also result in more heat loss by conduction and radiation from both the collector and drying cabinet, resulting in overall reduction in system efficiency. Mahapatra and Imre [34], and Garg and Prakash [9] have summarised the maximum allowable drying temperatures for a variety of agricultural food products.

Relative humidity of drying air is also crucial to the drying process. The ability of air to hold more moisture can be increased by either dehumidifying or heating the air (decreasing its relative humidity or increasing its moisture holding capacity)

before it enters the drying chamber or by heating it and thus increasing its evaporative capacity. If the exit air from the drying chamber still has considerable drying potential, mixing a fraction of the warm, humid exit air with fresh air and recirculating it in the dryer will help utilise part of the thermal energy in the exit air. The thermal efficiency of the system is thus improved [35]. Crapiste and Rotstein [7] note that the fraction of air recirculated can often be high, in the range of about 80–95%. Soponronnarit et al. [36] report a 50% drop in drying energy consumption while drying banana, when the fraction of air recycled was 95%.

3.1.4. Airflow rate

Airflow is another important parameter that influences the drying process. As the airflow rate is increased, the conduction and radiation losses may be small due to the smaller temperature rise. Drying efficiency may suffer at high airflow rates since air may not have adequate contact time with the food to increase its moisture content. Optimum airflow rate for solar dryers has been reported to be about 0.75 m^3/min per square meter of tray area [28].

Insufficient airflow can result in slow moisture removal as well as high dryer temperatures. However, the internal resistance to moisture movement in agricultural products is much greater when compared to the surface mass transfer resistance that the airflow rate beyond certain levels has no significant effect on the drying rate [37]. In natural circulation systems, airflow is primarily determined by the temperature rise in collector. Higher flow may be used at the beginning of drying and lower flow when drying enters the ‘falling-rate period’.

3.1.5. Dryer efficiency

Efficiency of the drying system is normally reported as dryer efficiency, heat collection efficiency or collector efficiency, specific moisture extraction rate and pick-up efficiency.

Collector efficiency or *heat collection efficiency* (η_{hc}) is a common measure of collector performance in a solar dryer ([38–41]). It is defined as:

$$\eta_{hc} = \frac{Q_a}{Q_c}. \tag{1}$$

Food dryers using flat-plate collectors and natural convection airflow have daily heat collection efficiencies ranging from about 40–60% [28].

Pick-up efficiency [23,42] determines the efficiency of moisture removal by the drying air from the product.

$$\eta_p = \frac{h_o - h_i}{h_{as} - h_i} = \frac{W}{\rho V t (h_{as} - h_i)}. \tag{2}$$

Pick-up efficiency generally decreases with decreasing moisture content in the product.

Drying (or system) efficiency indicates the overall thermal performance of the drying system, including collector efficiency and dryer (or drying chamber)

efficiency. The system efficiency of a solar dryer is a measure of how effectively the input energy (solar radiation) to the drying system is used in drying the product [27]. For natural convection solar dryers,

$$\eta_s = \frac{WL}{IA}. \tag{3}$$

System efficiency for forced convection solar dryers needs to take into account the energy consumed by the fan/blower. The following relation is then used:

$$\eta_s = \frac{WL}{IA + P_f}. \tag{4}$$

For hybrid dryers, which uses additional energy from a second source (e.g. biomass, LPG etc.), the system efficiency is given by

$$\eta_s = \frac{WL}{(IA + P_f) + (m_b \times \mathrm{LCV})} \tag{5}$$

where the term ($m_b \times$LCV) gives the energy input by the additional energy source.

Drying efficiency is commonly used to represent dryer performance [43]. Major factors affecting drying system efficiency include air temperature rise in the drying chamber, airflow rate, wind speed and collector/dryer design, which directly or indirectly relate to overall thermal losses in the system [28].

A few authors have also attempted to rate the performance of dryers using ‘Performance Indices’. *Evaporative Capacity* is one such performance index suggested by Jannot and Coulibaly [44], which considers the effect of ambient air temperature and humidity on the performance of a solar dryer. *Specific Moisture Extraction Rate* (SMER) is another performance index, which is used to describe the effectiveness of drying [29]. SMER is, in effect, the inverse of *specific energy consumption*, and is given by the ratio between the total moisture removed to the total energy input.

$$\mathrm{SMER} = \frac{\text{Rate of moisture removed from the product during the drying process}}{\text{Total energy input to the dryer}}. \tag{6}$$

Arinze et al. [45] report the performance of a heated-air hay dryer using *Drying Air Effectiveness*, which is given by the ratio of humidity of air at inlet (ambient) and exhaust from the dryer.

Drying energy consumption and specific energy consumption have also been reported by a few authors [43,46] while evaluating solar food dryers.

3.1.6. Quality of dried products

Drying usually affects the physical properties of the product and results in changes in size, shape, colour and texture. Many chemical and enzymatic conversions also take place during dehydration. Although these conversions are not always undesirable, some may make the product unpalatable.

Quality comparison between solar dryers is necessary as it could vary widely, depending on the drying temperature, dryer design, airflow rate and other parameters. Quality assessment of dried product usually includes assessment of sensory and nutritional parameters, and rehydration capacity [35,47,48].

3.1.6.1. Sensory parameters Sensory quality is a combination of different senses of perception coming into play in choosing and consuming food. Appearance judged by the eye, e.g. colour, size, shape, uniformity and absence of defects, is important in product quality assessment. Sense of taste is limited to sweet, sour, salty and bitter. Flavour involves the senses of taste, smell and feel. The characteristics of tastes could be estimated chemically, but their optima, in terms of consumer preference, varies.

Based on comparison of loss of flavour, vegetables are divided into three groups: (i) vegetables with volatile flavours (e.g. onions); (ii) vegetables with non-volatile flavours (e.g. peas, beans, cauliflower); and (iii) vegetables with volatile and non-volatile flavours (e.g. most roots such as carrots, turnips etc.). Although loss of flavour in dried foods is often due to volatile losses, chemical reactions (oxidation, browning etc.) contributes considerably to flavour deterioration [31].

3.1.6.2. Nutritional attributes These include chemical parameters such as ash and sugar content, ascorbic acid or Vitamin C, beta-carotene content, and acidity content [47] before and after drying. Higher ash content indicates contamination by dust; lower total (reducing and non-reducing) sugar content means lower quality due to higher drying temperatures; lower Vitamin C indicates nutrient loss due to higher drying temperatures and longer drying periods; higher acidity indicates quality deterioration due to fermentation.

3.1.6.3. Rehydration capacity Some dried fruits and vegetables are consumed after rehydration. When water is added, the product regains its original flavour, aroma, texture and appearance. However, the product will never return completely to its original level of moisture content. The extent to which it could regain its lost moisture is termed as rehydration capacity [49]. The closer it gets to its original moisture levels, the better will be its texture and appearance. Tissue damage in the product during the drying process is known to affect the rehydration capacity of the dried product. Tissue damage could occur during pre-treatments, handling, or subsequent drying, due to changes in the structure and composition of product tissue [50]. Khedkar and Roy [51] observed a higher rehydration ratio in cabinet-dried raw mango slices compared to sun-dried slices, and attributed this to less rupture of cells during cabinet drying (36.4%) than sun drying (67.3%). It has been generally observed that reducing the drying time and pre-treating the product using additives like salt and polyhydroxy compounds such as sugar and glycerol improves the rehydration quality of dried fruits and vegetables [31]. Pectin, an important cell wall and intercellular tissue component, is found to play a significant role in the rehydration capacity of dried fruits [52].

3.1.7. Cost of dryer and payback period

Financial viability is key to any solar dryer to successfully compete with other dryers. A financial analysis generally includes the cost of dryer (fixed cost), cost of drying (operating expenses) and payback. Solar dryers are generally capital intensive. They can be viable only if the annual cost of extra investment (on the solar dryer) could be balanced against fuel savings, or if the equipment cost could be reduced [31]. The user or dryer designer looks for a favourable combination of cost, energy efficiency, quality, and price of the final product [7].

Payback is the measure of time (number of days/months/years) it takes to recoup the total investment made on a dryer, in the form of operational cash inflow. Payback analysis does not measure the profitability of dryer as it does not take the service life of dryer into consideration. This is discussed in detail by Brenndorfer et al. [23]. Continued use of the dryer rather than seasonal use will decrease the drying cost and payback [45]. Economic analysis on a solar dryer should also incorporate the cost benefits due to improved quality, higher yields, less floor area and quicker drying [53].

3.2. Discussion

Table 1 summarises the performances of solar food dryers as reported by different authors. Most authors report the drying time/rate, capacity, temperature of air and quality, while quality of dried product, energy consumption and cost are reported less frequently. Other indicators such as solar aperture, drying efficiency and loading/unloading convenience are not usually reported.

An important step in any evaluation procedure should be the analysis of user requirements, from which relevant quality characteristics or parameters are deduced and broken down in terms of reportable attributes. After defining these attributes, actual testing may be carried out to perform measurements and to obtain values for the attributes. From the viewpoint of the user, the important attributes of solar dryers include cost, drying time, dryer capacity, product quality, handling convenience etc., as described in Section 3.1.

Dryer evaluation procedures reported in the literature mostly cover only a few selected parameters and a comprehensive evaluation incorporating all the relevant parameters does not appear to have been reported. Furthermore, a closer look at Table 1 suggests that certain additional aspects also require investigation in a systematic evaluation of a dryer.

It is observed [14, 16, 17, 47, 48, 52] that quality evaluation of dried product is nevertheless the single important aspect that has been reported with considerable inconsistency. Parameters considered for quality evaluation range from colour, texture and taste to rehydration capacity and nutritional values. There, however, seems to be no quantification of these quality parameters in most literature, which makes evaluation and comparison between dryers difficult and often misleading.

Successful testing and evaluation is not only a matter of the choice of instrumentation for the particular test environment, but also requires a detailed, correct and adequate reporting of the test results. Result reports (evaluation sheets) provide

details on the evaluation environment and observations made during the different testing exercises and provide an overall evaluation documentation. A standard evaluation environment and a common format for presenting evaluation results do not appear to exist at present. It is, therefore, necessary to follow a 'standard' evaluation procedure for evaluating solar food dryers.

4. A proposed comprehensive evaluation procedure

In view of shortcomings of present dryer evaluation methods as pointed out above, a comprehensive evaluation procedure has been proposed in this study; this includes:

1. improvements to certain aspects of existing procedures; and
2. introduction of new evaluation parameters.

The proposed procedure is expected to provide a common basis of comparison by quantifying the different parameters. Other parameters representing additional aspects of dryer performance have also been included; these are described in Section 4.2.

4.1. Proposed improvements to existing evaluation methods

4.1.1. Quality evaluation of dried product

Analysing the product quality involves comparing the results of sensory evaluation as well as rehydration, nutritive and chemical tests.

4.1.1.1. Rehydration The ability of the dried product to regain its original volume when soaked in water (rehydration) is a measure of product quality. Rehydration tests can serve to indicate the damage inflicted to the product caused by drying and pre-treatment. The common index used to express rehydration is the rehydration capacity or rehydration ratio, which is the ratio between the product weight after and before rehydration [48,71]. This is also termed as hydration coefficient by Ogwal and Davis [70]. Rehydration ratio has also been used to refer the ratio of weight after rehydration to the weight of dry matter [72]. The dried product will be graded best if it approaches the original fresh product volume.

Though a number of authors have reported on rehydration [20, 48, 51, 52, 70], there is no consistent procedure to measure rehydration. For example, while measuring re-hydration, the ratio between the dry material mass and water mass varies from 1:5 to 1:50, the temperature of rehydrating water varies from ambient to boiling temperature, the time of rehydration varies from 2 min to 24 h, and rehydrating water is still or occasionally stirred [51].

Luh and Woodroof [26] have suggested a rehydration measurement procedure for dried vegetables. Lewicki [51] proposed a method to calculate rehydration ability, which is based on the capacity of dried material to absorb water and to hold solubles

inside the product matrix. This takes into account the water absorption capacity (WAC) and dry matter holding capacity (DHC), and is given by:

$$\mathrm{WAC} = \frac{M_r(100-s_r)-M_d(100-s_d)}{M_o(100-s_o)-M_d(100-s_d)} \tag{7}$$

$$DHC = \frac{M_r.s_r}{M_d.s_d} \tag{8}$$

Both the indices express the extent of damage incurred to product tissue due to drying. The more the tissue is damaged, the smaller is the index.

Rehydration capacity (RC) of the dried product is the product of WAC and DHC, given by

$$\mathrm{RC} = \mathrm{WAC} \times \mathrm{DHC} \tag{9}$$

and lies between 0 and 1. This appears to be a more accurate measure of rehydration capacity and could be used as a standard.

Other parameters such as handling convenience, sensory quality, chemical analysis index, and overall dryer evaluation are all ranked using stars. For the purpose of consistency, rehydration capacity could also be represented using stars, two stars for rehydration capacity values given by Eq. (9) of 0–0.3, three stars for 0.3–0.5, and four stars for values above 0.5.

4.1.1.2. Sensory evaluation

4.1.1.2.1. Evaluation of colour Colour is one of the first quality attributes a consumer perceives in any food and so may influence the consumer's judgement of other attributes such as flavour. Change of colour is generally accompanied by flavour changes. Measurement of colour of a product implies either visual matching of product colour against standard colours or expressing product colour in terms of numerical dimensions using hue, saturation and lightness. While tintometers and spectrophotometers for measuring food colour may be expensive, visual matching against standard colours (e.g. colour dictionaries such as the dictionary of Maerz and Paul) may be used. In place of a colour dictionary, colour reproduced on secondary standards, such as painted test panels, rings and discs, may also be used. However, these secondary standards may fade over time/age. Illumination is of utmost importance while evaluating colour [48].

The Munsell color-order system [73] is a way of precisely specifying colors. The system is described in unabridged dictionaries, and recognized as a standard system of color specification in standard Z138.2 of the American National Standards Institute, Japanese Industrial Standard for Color JIS Z 8721, the German Standard Color System, DIN 6164 and several British national standards. Every color has three qualities or attributes: hue, value and chroma. Numerical scales have been established with visually uniform steps for each of these attributes. The Munsell Book of Color displays a collection of colored chips arranged according to these scales. Each chip is identified numerically using these scales. The color of a product can be identified by comparing it to the chips, under proper illumination and viewing conditions. The color is then identified by its hue, value and chroma (Munsell notation).

4.1.1.2.2. Evaluation of taste and aroma (cooking of representative samples) Samples from the rehydration test may be salted to taste, and cooked in steam or in a microwave oven. Once the best cooking time for each variety is established, it should be used for all samples of that variety so that texture may be judged comparatively. Luh and Woodroof [26] have proposed an overall sensory quality score for the dried product on the basis of observations and tests mentioned earlier (Table 2). Accordingly, individual quality parameters are allotted quantitative measures as per their degrees of importance in the overall quality of the product. Gallali et al. [47] and Grupp et al. [14] have reported similar evaluation procedures, but with different grading systems.

The product samples from the different dryers may be coded by a person not familiar with the dryers. Proper sampling is important in the quality evaluation process. Samples should be taken from homogeneous lots. Number of samples generally depends upon the sensory nature of the test product. Identity of the samples should be obscured by randomizing their order and by using codes which are unrecognised by the test crew. The test crew may then prepare the products separately but simultaneously in a microwave oven, and independently rank the products from the different dryers with regard to their colour, aroma and taste. Quality could be attributed with grades [49], from 2 to 12, where 2=poor or unacceptable quality and 12=excellent quality, and using stars, from single star (★) for poor quality up to five stars (★★★★★) for best quality [14].

Use of *Evaluation Cards* for product quality assessment has been proposed by Ranganna [48], for which a questionnaire or score card is prepared for each test (colour, flavour, taste, texture, aroma).

Quality ranking using stars can be applied for sensory evaluation for consistency with ranking of other parameters. Number of stars may be rounded to the nearest decimal value (e.g. 3.4★≈★★★; 3.8★≈★★★★).

Table 2
Existing and proposed grading system for sensory evaluation of quality

Parameter	Grading system of Luh and Woodroof	Proposed evaluation rank		
	Max. possible points per parameter	Best quality (maximum grade)	Medium quality	Poor quality
Rehydration	20	★★★★	★★★	★★
Colour	10	★★★	★★	★
Texture	30	★★★★★	★★★★	★★★
Flavour	30	★★★★★	★★★★	★★★
Aroma	10	★★★	★★	★
Taste		★★★★	★★★	★★
Total	100			
Average		★★★★	★★★	★★

4.1.1.3. Chemical tests The nutritive value of food is generally affected by the dehydration process. Vitamins A and C are destroyed by heat and air. Using a sulfite treatment prevents the loss of some vitamins, but causes the destruction of thiamin. Blanching vegetables before drying (to destroy enzymes) results in some loss of Vitamin C, B-complex vitamins and some minerals because these are all water-soluble. On the other hand, blanching does reduce loss of vitamins A, C and thiamin during dehydration and storage [74].

Nutritive values, ash content and acidity can be determined by simple chemical analysis. A new chemical analysis index is suggested for evaluating product quality through chemical rests. This index may also be ranked using stars (★). Suggested index values for various results of chemical analysis of the dried product sample are presented in Table 3.

Of the five parameters considered in the chemical analysis, Vitamin C and beta-carotene contents in the product are given a higher weight in terms of nutritional value. Therefore, the number of stars for their contents in the product are rated high as compared to other parameters.

Net quality grade can be determined by averaging the quality grades of sensory evaluation and chemical tests.

4.1.2. Drying time required to reach 15% product moisture content

One important parameter in the performance evaluation of solar food dryers is drying time, which can be used to compare different dryers (for the same product and similar test conditions). During drying of food products, it is difficult to monitor closely and stop the drying operation when the product final moisture content reaches exactly the same value in all the individual dryers. However, for a rational comparative evaluation, it is worthwhile considering a single final moisture value for all the dryers under evaluation. This can be done by analysing the drying curve (product moisture content vs. time) for each dryer, and estimating the drying time taken by individual dryers to arrive at a particular final moisture content. This value may be fixed at slightly higher than the final moisture content that can be reached by the product(s) tested in the dryers if drying is complete. Typically, this value can be taken as 15% (w.b) for most fruits and vegetables while a value of 20% may be considered for those fruits and vegetables which will not dry to moisture levels of

Table 3
Proposed quality evaluation based on chemical analysis index

Parameter	Evaluation ranking		
	High (maximum grade)	Medium	Low
Ash content	★★★	★★	★
Total sugar content	★★★	★★	★
Vitamin C (ascorbic acid) content	★★★★★	★★★★	★★★
Beta-carotene content	★★★★	★★★	★★
Acidity	★★★	★★	★
Average ranking	★★★★	★★★	★★

less than 20%. Any other appropriate limit for final moisture content may also be considered depending on the product. Thus, the drying time taken by dryers to reduce the product moisture content to 15% (w.b) is an indicator of the dryer efficiency.

4.1.3. Drying system efficiency during drying up to 15% product moisture content

As detailed in Section 3.1.5, drying system efficiency takes into account the weight of moisture evaporated from the product and the energy input to the drying system during the drying time. For the same reason mentioned in the earlier section, drying time in this case should be the time taken by the product to reach the 15% (or as applicable) moisture content. While measuring the system efficiency, weight of moisture evaporated and energy input to the system should be estimated for this drying time for all the dryers under evaluation. This would mean a consistent comparison between the different dryers under evaluation.

4.1.4. Loading density per unit area of solar aperture

Loading density is usually a measure of how much product is loaded per unit tray area. However, dryers, such as the cabinet dryer, often have large tray areas as their drying cabinet design allows staggering of trays one above the other. The definition of loading density in such cases may be misleading as a straight comparison between a cabinet dryer and another type of dryer of comparable size, which does not allow staggering of trays, leads to large variations in the quantity of product loaded. Loading density, therefore, can be presented in terms of kg of fresh product per square meter of solar aperture.

4.2. Additional parameters proposed in the evaluation of solar dryers

The parameters reported in Table 1 do not seem to provide sufficient information for a systematic evaluation of solar dryers. Heat collection efficiency, for example, is not precise unless the total area receiving solar radiation (solar aperture) is known. Restrictions in available floor space may limit the usage of a particular type of dryer. There are many socio–economic factors, particularly of a local nature, which must be considered in the evaluation process [23], and inclusion of certain additional parameters in the overall evaluation process would contribute to the evaluation of dryer performance and application. These include: (i) solar aperture; (ii) first day drying efficiency; (iii) maximum drying temperature at no-load and with load; (iv) duration of drying air temperature 10 (or 15)°C above ambient; (v) loading and unloading time; (vi) floor space and skilled technicians/operators requirement; and (vii) uniformity of drying, ease of dryer construction, safety and reliability.

4.2.1. Solar aperture

The area of the collector or tray receiving solar radiation (solar aperture) could be an important consideration in the estimation of drying efficiency for mixed-mode dryers in which the product receives solar radiation directly as well as indirectly. Solar aperture indicates the total solar radiation collection area. In mixed-mode dry-

ers, it should include the collector area and the spread area of the product receiving direct solar radiation.

4.2.2. First day drying efficiency

Drying efficiency markedly varies with the moisture content of the product. For the same energy input, drying efficiency decreases when the drying process shifts from constant-rate drying to falling-rate drying. Efficiency calculation during the constant-rate drying period of the product could offer a more consistent evaluation of the dryer thermal performance. However, due to the absence of a constant-rate drying period in many fruits and vegetables [80] and the difficulty in observing the change from constant-rate drying to falling-rate drying with products having a definite constant-rate drying period, system efficiency during the first day of drying may be reasonably taken as a consistent measure of the thermal performance of a dryer. This would be useful to compare the performance of different dryer types.

4.2.3. Maximum drying temperature at no-load and with load

Temperatures in the range of 50–60°C are recommended for drying temperature-sensitive products like fruits and vegetables. Temperatures up to 65°C may be used at the beginning, but should be lowered as food begins to dry. For at least the last hour of the drying period, the temperature should not exceed 55°C. Any higher temperature will most probably affect the quality of the product [33]. It is, therefore, important to consider the maximum drying temperature of a dryer under loaded condition.

Maximum drying temperature attained in a dryer under loaded condition varies with the product type and moisture content of the product loaded. It does not give a general consistent measure of dryer performance. Maximum drying temperature *under no-load condition* could therefore become a measure of dryer performance. This gives the maximum temperature that could be attained inside the dryer and is an indication of heat collection efficiency and thermal insulation of the dryer.

4.2.4. Duration of drying air temperature 10 (or 15)°C above ambient

From the drying efficiency figures for forced convection dryers, it is difficult to recognise whether drying was influenced by large airflows with a small temperature rise or vice versa. Under similar radiation levels, efficiency values for two dryers can be similar even if the airflow rates are different. Consideration of this phenomenon may be useful for a dryer designer to improve the dryer performance, or for a user, to select a particular drying condition for a specific product. Since a temperature elevation of at least 10–15°C from the ambient is required for effective drying to take place, duration of drying air temperature 10°C (or 15°C, depending on the site location of the dryer) above the ambient temperature may be an useful indication on the collector/dryer performance. This may be measured under load as well as no-load conditions, and could indirectly indicate the heat collection efficiency of the dryer.

4.2.5. Loading/unloading time

This factor is generally neglected in the evaluation of dryers, but the time for loading and unloading is an important consideration in the appropriate design of commercial dryers. The requirement of high labour cost is an important operating expense which could influence the economics of drying. A record of loading and unloading time of dryers (in minutes) per kg of product (fresh/dried) is an additional parameter for comparative evaluation of dryers.

4.2.6. Other parameters

Other aspects that may need consideration for some users and be useful for comparative evaluation of dryers are as follows.

1. Uniformity of drying: in dryers with long or tall drying chambers, where the drying air travels considerably before exiting, the product at the tail end often dries slower than that at the inlet. This could result in non-uniform drying.
2. Floor space requirement: in certain locations, especially in hilly-terrain, identifying flat land for installing dryers may be often difficult, and may be an important consideration in the selection of dryers.
3. Requirement of skilled technicians and operators: this may be an important consideration in certain types of solar dryers (e.g. solar-biomass hybrid dryer), where control and operation of the drying system may require some expertise.
4. Ease of construction: availability of skilled manpower for construction assumes greater importance in remote villages where availability of construction materials and expertise could severely weigh against a specific dryer.
5. Safety and reliability.

4.3. Evaluation methodology, instrumentation and measurement

The evaluation methodology for thermal performance consists of: (a) preparation of dryers and product; (b) installation of measuring and recording instruments; and (c) experimentation.

Preparation of the dryer involves ensuring proper functioning of the dryer. Cover glazing must be thoroughly cleaned, and black coating for the solar collector should be checked and repainted if necessary.

The product to be tested may have to be prepared in some cases. This may involve pre-drying processes, such as peeling, cutting, slicing, coring, pitting, trimming etc., and pre-treatment methods, such as blanching, sulfiting, salting, alkaline dip, heating, cooking, freezing and thawing. Product information, namely variety, kind or breed, maturity, and pre-treatment, should be noted. Details on the pre-drying processes and pre-treatment methods are essential for maintaining consistency among the different products used in different dryers.

The dryer test site should be free from shadows during the testing period.

Instrumentation and measuring equipment on the dryer and at the test site generally include temperature and relative humidity sensors, pyranometers, anemometers and dataloggers. The following measurements are required.

1. Physical features of the dryer such as collector area, collector tilt, solar aperture, tray area and number of layers need to be recorded. Loading density can then be estimated by the following relation:

$$\text{Loading density} = \frac{\text{Weight of fresh product loaded in the dryer (in kg)}}{\text{Total solar aperture (in m}^2\text{)}}. \qquad (10)$$

2. Global solar radiation on the plane of solar collector or absorber is measured using pyranometers. Many commercial pyranometers are available, which meet the requirements of WMO standards. Simple Dome Solarimeters are easy to use, and once calibrated, retain their accuracy for long periods [23].
3. Drying time and loading/unloading time can be measured by a clock.
4. Airflow rate can be measured with a hot-wire anemometer.
5. Temperature and relative humidity could be measured using appropriate sensors and recorded in a data-logger. In cases where a data logger is not available, these data may be recorded manually every 30 min or one hour intervals by a thermometer and hygrometer, respectively. The temperature and relative humidity values recorded could be summarised to obtain the average or mean value, the maximum and minimum temperature and the duration of air temperature 10 (or 15)°C above ambient.
6. The weight of fresh product loaded in the dryer and of dried product at the end of drying need to be noted.
7. The moisture content of the products may be determined at regular intervals (e.g. 1 h), for continuous observation of the drying process. Samples for moisture measurement should represent the average moisture content of the whole lot, and therefore be picked carefully. A convenient practice is to take samples from four or six locations in the dryer and averaging them. The American Society of Agricultural Engineers standards for measuring the moisture content of grains, seeds, tobacco, and a few vegetables such as carrot, cabbage, onion, radish and turnip [75–78] could be used. However, moisture measurement in fruits and most other vegetables are not included. Standards have also been developed for drying of grains and crops by ASAE [75,79], but not for fruits and vegetables.

Heat collection efficiency, pick-up efficiency, first day drying efficiency and the overall dryer or drying efficiency can be estimated from Eq. (2) to (4).

Two types of sensors are generally used to measure temperature: one, to measure surface temperature (surface probe) and the other to measure air temperature (air probe). Calibrated sensors should be installed at the air inlet side, exit side, and at several locations in between, and their exact locations may be decided depending on the type of dryer and the data requirement. While fixing surface probes, it is important to ensure proper physical contact between the sensor and the surface. Air probes should be fixed carefully so as not to touch any metal/product surface.

Temperature and humidity data may be recorded as closely as possible (typically every 5 min), depending on the memory constraints of the data logger. To facilitate comparison of results among the different dryers, the frequency of measurement should be the same for all dryers being tested.

When the drying process extends over two or more days, it is common practice to unload and store the product indoors at the end of the day, to avoid overnight re-wetting. Products in such cases should be stored in dry and clean polythene bags, so as not to affect the moisture and quality levels of the product. The bags should be made airtight to avoid contact of the product with atmospheric air.

At the end of drying, the quality of dried product should be assessed in terms of rehydration, sensory evaluation and chemical tests, as described in Section 4.1.1.

Information on the financial viability of the dryer should be estimated based on the cost of the dryer, the price of dried and fresh product, operation and maintenance costs for drying unit product and payback.

Table 4 lists the parameters reported in existing dryer evaluation procedures (from

Table 4
Comparison of parameters reported in existing and proposed evaluation procedures

Sl. No.	Evaluation parameter reported in existing evaluation procedures	Evaluation parameter reported in proposed evaluation procedure
I. Physical features of dryer		
1.	Type, size and shape	Type, size and shape
2.	Collector area	Collector area and solar aperture
3.	Drying capacity/loading density (kg/unit tray area)	Drying capacity/loading density (kg/unit aperture area)
4.	Tray area and number of trays	Tray area and number of layers
5.	Loading/unloading convenience	Loading/unloading convenience
6.		Loading/unloading time
7.		Handling, cleaning and maintenance convenience
8.		Ease of construction
II. Thermal performance		
9.	Drying time/drying rate	Drying time/drying rate up to 10% product moisture content (w.b)
10.	Dryer/drying efficiency	Dryer/drying efficiency until product moisture content reaches 10% (w.b)
11.		First day drying efficiency
12.	Drying air temperature and relative humidity	Drying air temperature and relative humidity
13.		Max. drying temperature at no-load and with load
14.		Duration of drying air temp. 10°C above ambient
15.	Airflow rate	Airflow rate
III. Quality of dried products		
16.	Sensory quality (colour, flavour, taste, texture, aroma	Sensory quality (colour, flavour, taste, texture, aroma)—quantified for easy comparison
17.	Nutritional attributes	Nutritional attributes—quantified for easy comparison
18.	Rehydration capacity	Rehydration capacity—consistency in presentation
19.		Uniformity of drying
IV. Economics		
20.	Cost of dryer and payback	Cost of dryer, cost of drying and payback
V. Other parameters		
21.		Floor space requirements, skilled technician and operator requirements, and safety and reliability

Table 1), and compares them with the proposed standard evaluation procedure. Several additional parameters discussed above have been included in the proposed procedure to provide a comprehensive picture on the dryers under evaluation.

4.4. Proposed evaluation sheet

Table 5 presents a sample evaluation sheet based on the proposed procedure. A direct comparison of the parameters recorded in the evaluation sheet would reveal the comparative merits of one dryer over the others at similar test conditions, and would help users to select dryers for their requirements.

Drying curves for the product based on the actual drying conditions are plotted with product moisture content on the ordinate and time on the abscissa. The drying curve for the product dried in the open sun should also be plotted on the same graph, for comparison.

Table 5
Evaluation results of two dryers compared to open sun drying

(**Sample Evaluation Sheet**)

Product:
Initial Moisture Content: (% w.b)
Global radiation on the plane of solar collector for day1/day2/day3/day4 etc. (MJ/m2)
Average ambient temperature for day1/day2/day3/day4 etc. (°C)
Average ambient relative humidity for day1/day2/day3/day4 etc. (%)

Parameter	Dryer 1	Dryer 2	Open Sun Drying
Quantity loaded (full load), kg			
Loading density, kg per m^2 of solar aperture			
Collector area, m^2			
Collector tilt (°)			
Solar aperture, m^2			
Tray surface area, m^2			
Airflow rate, m^3/h			
Drying time, upto 10% moisture content (m.c), (including nights), hr			
Overall drying efficiency, upto 10% m.c., %			
First day drying efficiency, %			
Heat collection efficiency, %			
Pick-up efficiency, upto 10% m.c., %			
Average temp. and RH of exit air: day1/day2, °C, %			
Max. drying temp. at no-load, °C			
Max. drying temp. with load, °C			
Duration of drying air temperature 10°C above ambient (no-load), hr			
Quality of dried product (refer Tables 2 and 3)			
Loading/unloading convenience			
Cost of dryer, US$			
Cost of drying, US$/kg fresh			
Dryer payback period, years			

5. Conclusion

A review of existing evaluation methods and parameters used for the evaluation of solar dryers has been carried out and their limitations discussed. Based on the review, a comprehensive procedure has been developed. Additional parameters have been included in the proposed procedure. The results of the observations could be reported using evaluation sheets, which together with the graphs representing the drying curves and cumulative drying energy consumption could provide a complete picture of the absolute and comparative performance of the dryers.

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